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PV power conversion and short-term forecasting in a tropical, densely-built environment in Singapore

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ABSTRACT

With the substantial growth of solar photovoltaic installations worldwide, forecasting irradiance becomes a critical step in providing a reliable integration of solar electricity into electric power grids. In Singapore, the number of PV installation has increased with a growth rate of 70% over the past 6 years. Within the next decade, solar power could represent up to 20% of the instant power generation. Challenges for PV grid integration in Singapore arise from the high variability in cloud movements and irradiance patterns due to the tropical climate. For a thorough analysis and modeling of the impact of an increasing share of variable PV power on the electric power system, it is indispensable (i) to have an accurate conversion model from irradiance to solar power generation, and (ii) to carry out irradiance forecasting on various time scales. In this work, we demonstrate how common assumptions and simplifications in PV power conversion methods negatively affect the output estimates of PV systems power in a tropical and densely-built environment such as in Singapore. In the second part, we propose and test a novel hybrid model for short-term irradiance forecasting for short-term intervals. The hybrid model outperforms the persistence forecast and other common statistical methods.

1. Introduction

The growth of renewable energy photovoltaic (PV) systems deployment worldwide has been considerable through the past one and a half decades. The worldwide installed capacity was a mere 1 GW_p in the year 2000, but has reached 178 GW_p by the end of 2014 [1]. Singapore, located one degree north of the Equator (1.37°N, 103.75°E), has seen an exponential growth of solar PV deployment starting from around 2009, having reached 33 MW_p by the end of 2014 [2]. While today's deployed PV fleet of ~700 systems contributes to less than 1% of the electricity needs of the country [3], Singapore's PV contribution potential for future energy (not instant power) needs is estimated at 10–20% by 2050 [4].

As penetration rates for solar PV increase in countries around the world, for example Italy (~8% of the total electricity generation), Germany (~6%) and Greece (~6%) [1], forecasting the solar irradiance resource becomes more and more critical for assisting power system operators in management of the electricity grids, whether for short-term (systems reserves, dispatch), or long-term applications (for unit commitment, scheduling). Most of the forecasting in literature focuses on intra-day (a few hours ahead) or day-ahead time frames. The large volumes of PV deployed in some countries, however, raise the risk of potential grid imbalances due to the variable nature of the solar resource [5,6].

Electricity in Singapore is predominantly (~97%) generated via gas turbines [7], widely using combined-cycle fed by piped natural gas from Malaysia and Indonesia, and more recently, from a new liquefied natural gas complex, allowing alternative sourcing of fuel from the global market. The trade interval for electricity is 30-min, which fits well with short-term solar irradiance forecasting efforts. Irradiance forecasting alone, however, is not sufficient for power system operators as they require PV power generation forecasts, which then also calls for accurate conversion models of irradiance

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into PV power.

As previous research has attempted [8,9], and also as discussed by IEA Task 14's (High Penetration of PV Systems) [10], a number of PV systems in a given country/region may act as baseline for further up-scaling in an attempt to estimate the power output of an entire fleet of photovoltaic systems. Up-scaling entails the use of a certain number of PV facilities as a representation of the entire system fleet of a city, region or country of interest. Such estimations take into account a few assumptions which, when applied in a tropical environment setting, could lead to conversion errors as shown later.

In this work, the challenges of accurately converting irradiance values into PV power output will be discussed for a tropical location in Singapore. Those include a model for conversion from global horizontal irradiance (GHI) into in-plane irradiance (G_{mod}) and, from there, an advanced PV system power output conversion, from in-plane irradiance all the way to the final generated kW by the solar system. This also includes the influences of PV module temperatures, which is the single-largest loss factor in PV systems in the tropics. A third effect is shading by neighboring buildings, which is often unavoidable in a highly-dense city environment such as in Singapore and obviously will affect a system's power output. Fourthly, and often not taken into account, are the influences of system degradation over time when modeling their future behavior. Finally, variations in irradiation at ground level caused by air pollution is addressed, which becomes more and more an issue in high population-intensive city centers [11].

Since the majority of the publications on both PV power conversion as well as irradiance forecasting have focused on locations where PV has flourished in the past nearly two decades (i.e. mainly temperate climates), the work presented here aims at being novel and relevant for future PV grid implementation efforts in countries with hot and humid weather conditions as those found in Singapore.

Section 2 presents a review of existing literature on PV power generation output modeling, including challenges which are perceived to be relevant for the integration of variable solar power into tropical grids. Section 3 summarizes literature on solar irradiance forecasting, with a focus on short-term applications and on previous research efforts achieved in the tropics. Section 4 describes the experiments for this investigation, followed by Section 5 showing results and discussions of the outcomes. Section 6 presents the main conclusions, with Section 7 giving an outlook for the future of PV power forecasting and system up-scaling in the tropics.

2. PV power conversion and forecasting

2.1. PV power conversion

Heydenreich et al. [12] tested a PV power model using three parameters (a, b, c) to characterize the efficiency curves of PV devices. The authors applied flash testing to several crystalline silicon modules in order to empirically derive the appropriate parameters. The formula for the model follows:

$$\eta_{mpp,25}(G_{mod}) = a\,G_{mod} + b\ln(G_{mod}+1) + c[\ln^2(G_{mod}+e)/(G_{mod}+1) - 1] \qquad (1)$$

where $\eta_{mpp,25}$ is the efficiency of the PV module at 25 °C at its maximum power point (MPP) efficiency, G_{mod} is the irradiance on the plane of the array, and a, b, c the model values. Equation (1) yields the module MPP efficiency only at a device temperature of 25 °C. For the efficiency adjustment at other temperature ranges, Equation (2) needs to be applied:

$$\eta_{mpp}(G_{mod}, T_{mod}) = \eta_{mpp,25}(G_{mod})[1 + \alpha(T_{mod} - 25°C)] \qquad (2)$$

where η_{mpp} is the efficiency of the photovoltaic device at a given temperature, T_{mod} is the module temperature and α is the temperature coefficient of the module power point (MPP). A common value for α in crystalline silicon modules is $-0.0045\ °C^{-1}$. In order to estimate module temperatures, the following equation is valid, for the condition of no wind, which is often the case found in Singapore:

$$T_{mod} = T_{amb} + \gamma G_{mod} \qquad (3)$$

where T_{amb} is the ambient temperature, with γ commonly referred to as the Ross coefficient [13], which is influenced by the surrounding environmental conditions, including the mounting type. A typical value used for γ is $0.020°Cm^2W^{-1}$ for ground-mounted installations with good ventilation [9].

State-of-the-art PV systems in Germany are able to achieve close to 90% performance ratio (PR), with temperature-related losses accounting for ~20% and ~45% of the total system losses for winter and summer months, respectively [14]. PR is a measure of quality of a PV installation and a classic metric used to compare PV system performance across different locations. It uses the standard test conditions nameplate capacity of a solar system as normalizing factor and takes into account a theoretical full DC conversion on the photovoltaic device, with all other losses accrued associated with post photovoltaic effect conversion. PR is defined in the IEC 61724 standards for PV system performance monitoring.

Stemming from the PV system modeling based on Equations (1)–(3), a recent study on PV simulation using 29 PV systems in Germany and Spain showed good agreement with real-world data, with the differences in yield estimations and actual field outputs mainly arising from changes in irradiance differences due primarily to solar brightening (the irradiation databases, based on past decades records, present lower annual irradiation levels than recent records). The uncertainty of yield predictions today in Europe is approximately 8%, as shown in Ref. [15].

2.2. PV power forecasting

In order to predict the power generation of PV systems for assessing the impact of PV systems on the electric power system, it is important to carry out so-called spatial-temporal forecasting. In the absence of a central database of the physical locations and system parameters (size, tilt/orientation, technology, age of the PV systems), it is necessary to use a representative number of installations and to up-scale the results to the desired power system coverage zone. Only then the forecasting outputs are meaningful.

Based on numerical weather prediction forecasts for the entire Europe zone, Lorenz et al. [9] have performed such up-scaling routine for PV systems in Germany using a baseline of representative installations in order to predict future system output for the many thousands of other systems in the country. Input parameters were forecasted irradiance up to two days ahead, in hourly resolution intervals, and using ambient temperature to determine the module temperature (as per Equation (3)), as one of the assumptions in the model. 4–5% root mean square errors for intra-day and day-ahead forecasts for large transmission areas were achieved in the study.

Researchers in Japan conducted a comprehensive investigation on day-ahead PV power forecast based on more than 700 hundred PV systems [16]. The study found that for systems tilted above 40°, higher forecast errors were identified.